Hardware enclaves & oblivious computation

Slides adapted from here

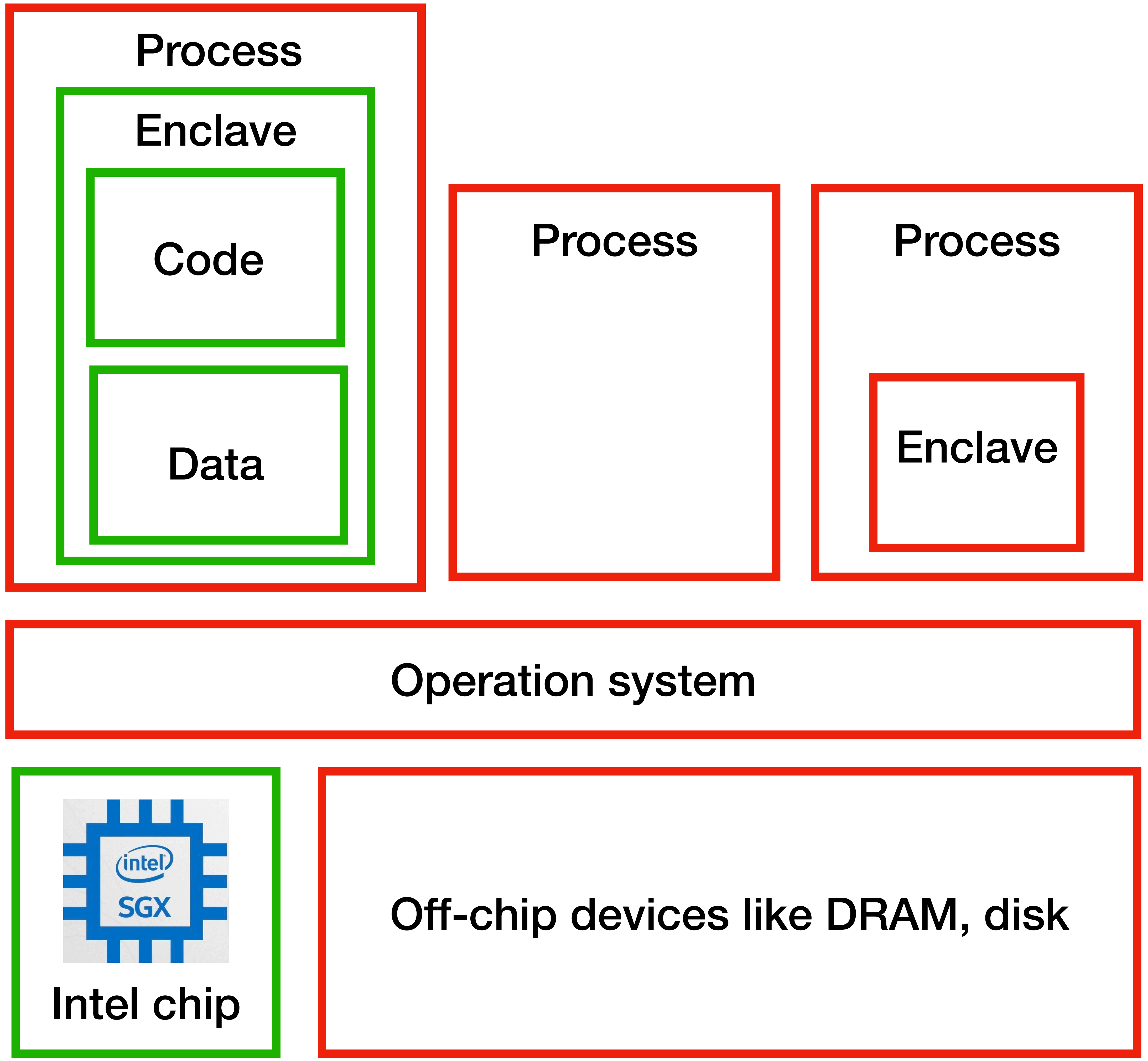
Hardware enclaves

- An alternative way to compute on encrypted data
- Hardware abstractions for distributing trusted execution to untrusted platforms

Real world threats to trusted execution

- Malicious software
  - Rootkits in OS, malicious kernel
- Cold-boot attacks
  - Memory modules do not immediately lose data after loss of power
  - Attacker with physical access can perform a memory dump of a machine's RAM by abruptly rebooting a target machine and then booting a re-installed OS from a flash drive
  - Literally **cold** as liquid nitrogen can be used to prolong data remanence
  - Software-based disk encryption can be circumvented

Hardware enclaves architecture



Attacker can compromise almost the entire server-side software stack

Trusted CPU

- Content is stored unencrypted in registers and cache (cannot be read by the adversary)
- Adversary cannot change enclave program execution
  - Any interruption/exception triggers an asynchronous exit (AEX) operation
  - Enclave context is saved in the EPC, registers are erased, and control flow is returned to the external program

Enclave page cache

- Enclave pages are encrypted and stored in Enclave Page Cache (EPC)
- All enclaves share this space, but pages are encrypted under different keys
- Memory encryption engine (MEE) encrypts all evicted data from the cache
- EPC pages can also be evicted to main memory by the OS
- Content integrity is protected by MACs over pages plus a Merkle tree
- EPC pages used to be limited to 93.5 MB
    - Recent Icelake SGX has up to 1 TB of EPC!

Remote attestation

- Each enclave has a set of unique keys that are generated by a root secret embedded in the trusted CPU hardware
- Enclave produces a signed message, including a *measurement* that identifies the loaded program
  - Group signature scheme that preserves anonymity of the signers
- The signature can be verified by a remote user using the trusted Intel Attestation Service (IAS)
  - Group public key used to verify enclave is genuine

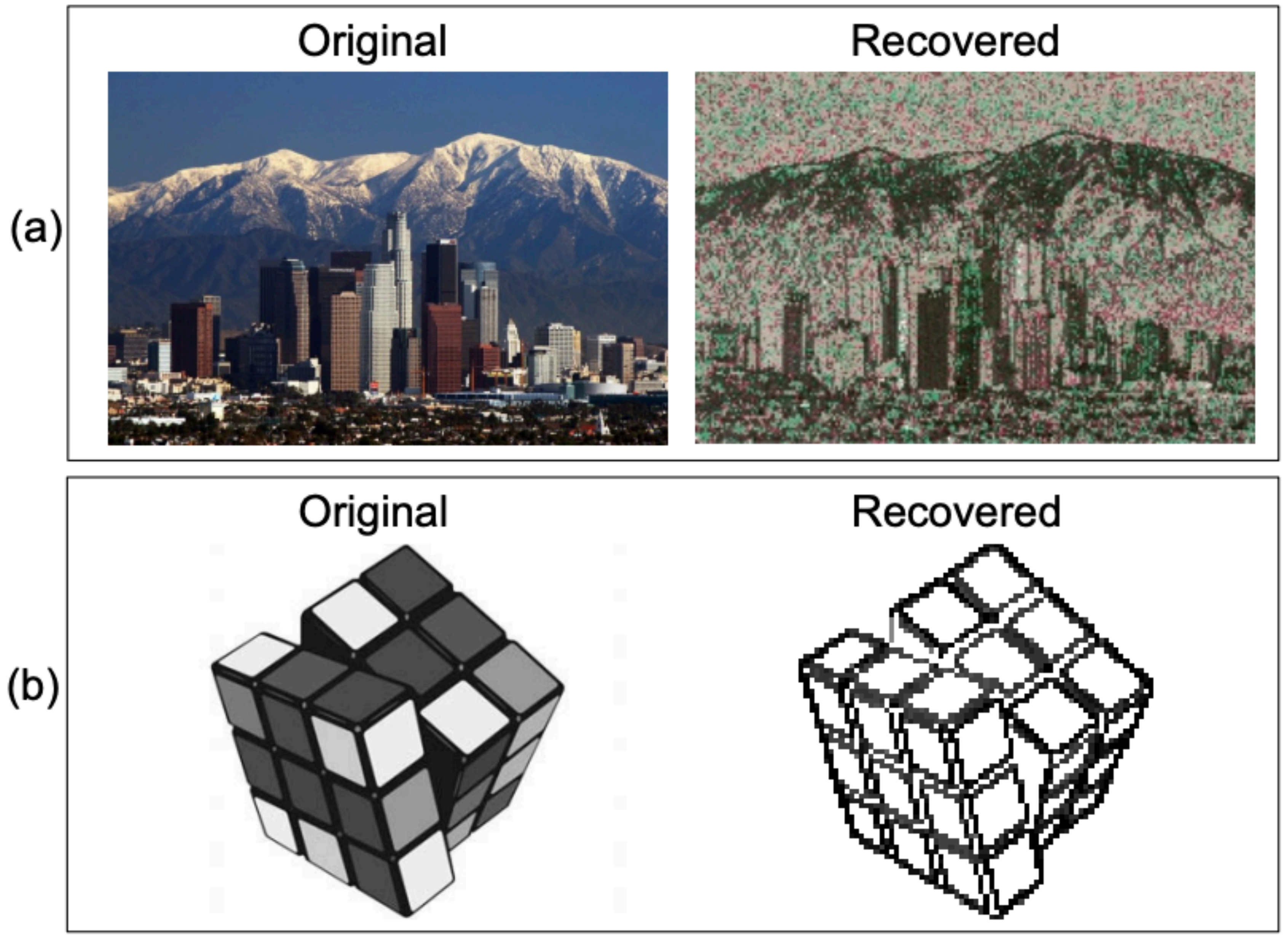
Enclaves are widely available in the cloud

- Azure supports SGX
- GCP supports AMD SEV (Secure Encrypted Virtualization)
- AWS supports Nitro (hypervisor-based)

Enclaves are prone to side channel attacks on encrypted data

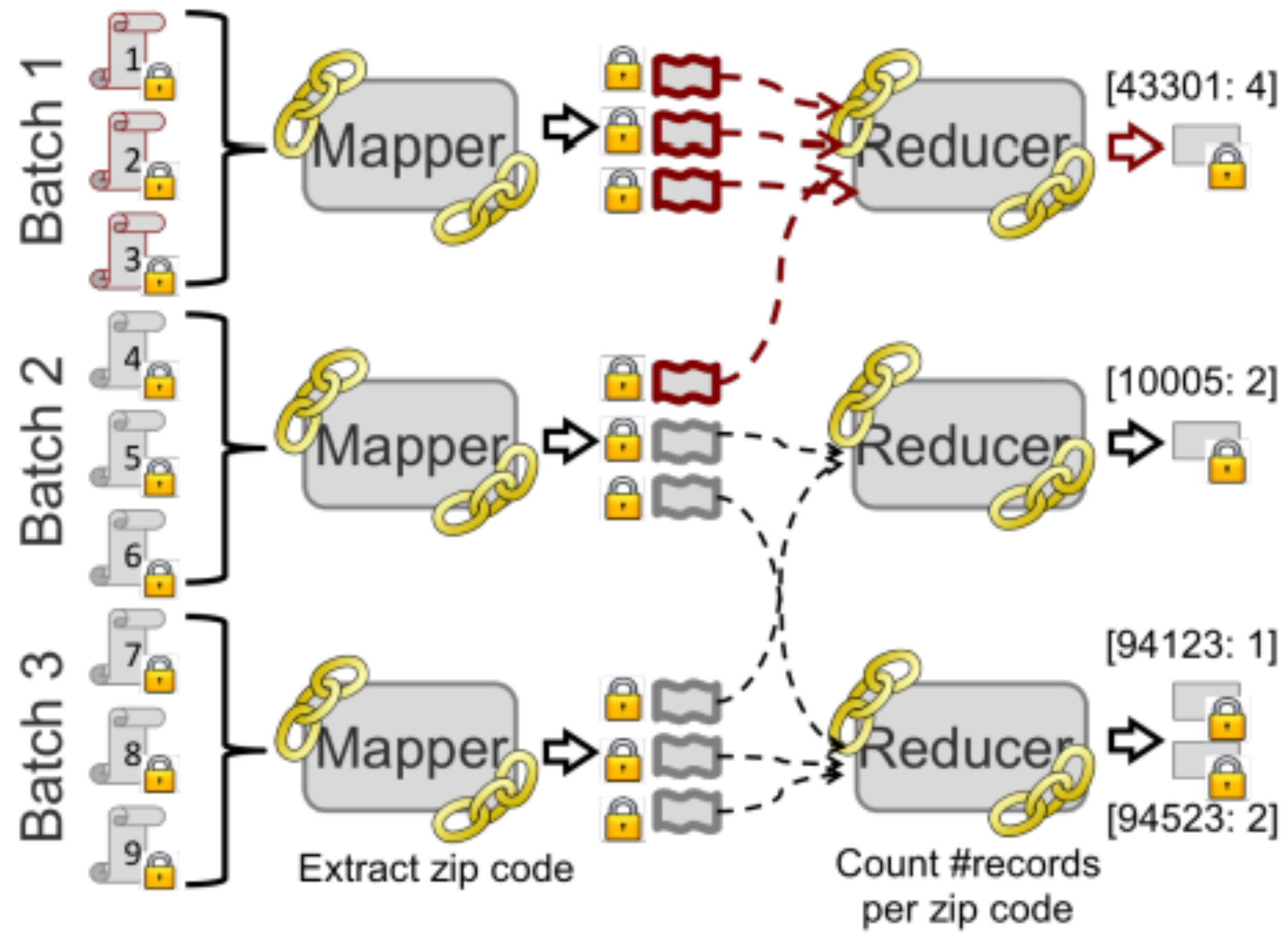
Memory side channels

- OS is still in charge of resource management
- OS controls page table (mapping between virtual pages and physical pages)
    - Can reclaim physical pages (swap page to disk) and restore page mappings (load physical page from disk)
    - OS must know the *virtual base address* of the page at which the page fault occurred (though not within a page)
- Controlled-leakage channel attack shows how the OS can trigger page faults
    - Extract text documents from font rendering engine & spell checker
    - Obtain outlines of JPEG images decompressed by libjpeg



Network side channels

- SGX only meant to handle single machine applications
- Distributed applications need network communication
- A powerful attacker can analyze traffic patterns even if communication is encrypted
- This paper attacks VC3 (a MapReduce system on SGX) by observing volume of encrypted communication



How to protect against access pattern leakage?

- Regular computation leaks due to *data-dependent access patterns*
- Access patterns will change depending on the data content, revealing information even if all data content is encrypted
- *Oblivious algorithms* can be used to protect against such leakage

Oblivious sorting

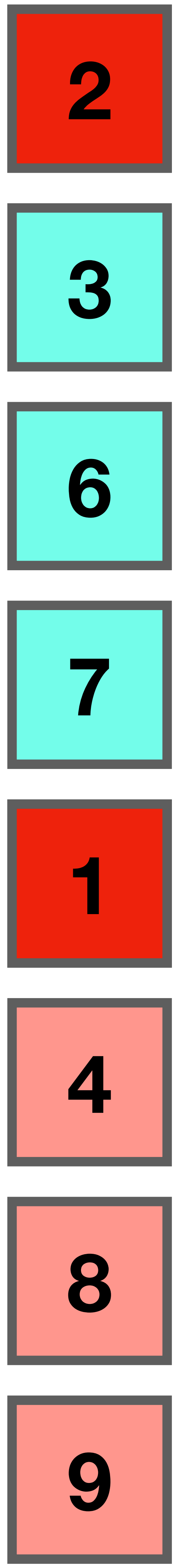
- Comparison-based sorting, but fix the number of comparisons
- Also called a *sorting network*
- Batcher's algorithm
  - Sort the first half of a list, and sort the second half of that list
  - Sort the odd-indexed values, then even-indexed values
  - One more comparison-switch per pair of keys
  - Proof of security?

Batcher's algorithm correctness

- **Theorem:** Batcher's algorithm described on the previous slide results in a sorted list.

- **Proof:** Let the list's size be n where n is a multiple of 4. Denote the list as X. If two halves have been sorted separately, then for all elements between 1 and n except for X_1 and $X_{n/2+1}$, $X_{i-1} \leq X_i$. We call X_{i-1} the **predecessor** of X_i.

  Both 1 and $n/2 + 1$ are odd, so the above is true for every even-indexed value, and true for every odd value except for two.

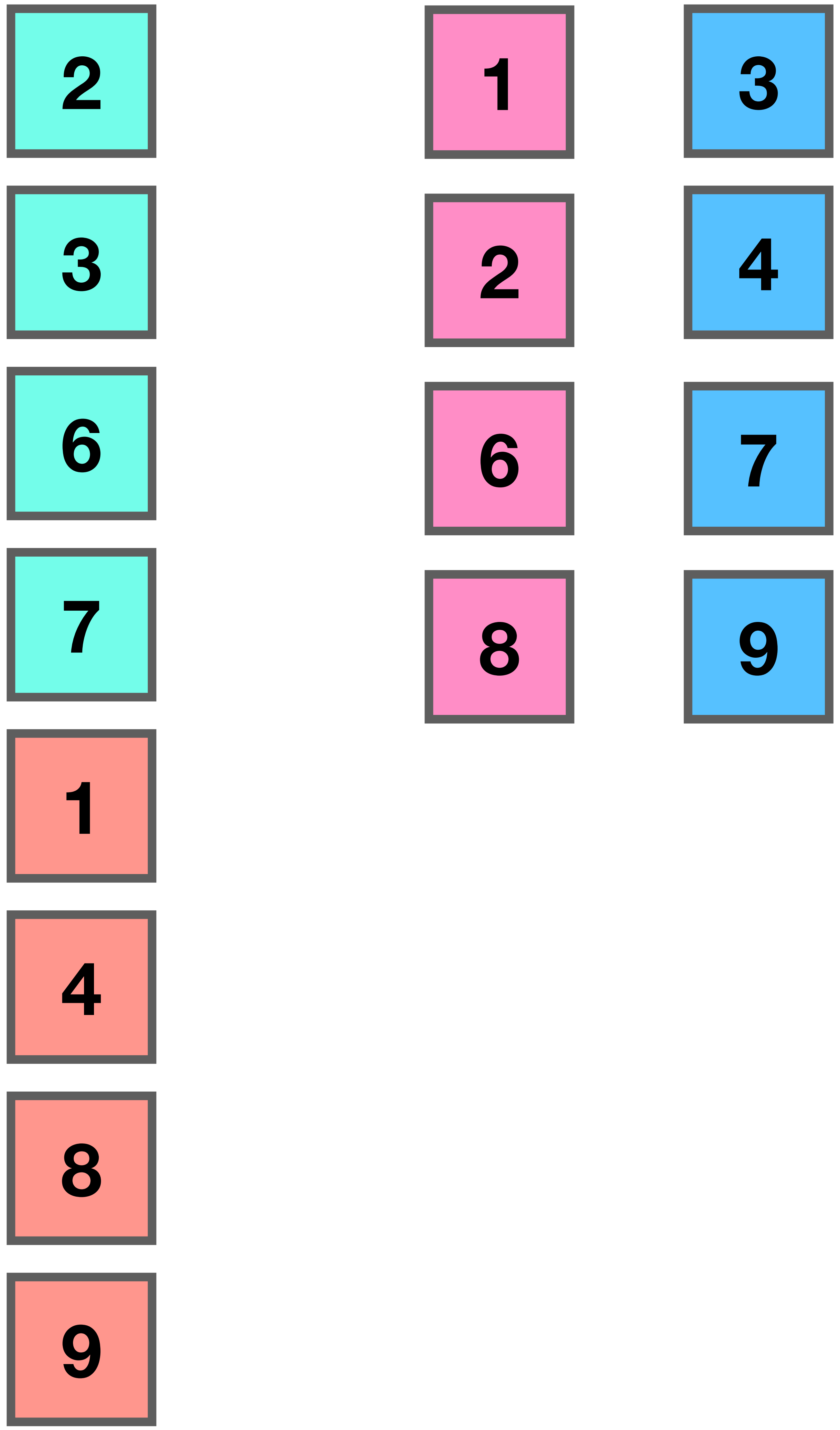


Batcher's algorithm correctness

- **Theorem:** Batcher's algorithm described on the previous slide results in a sorted list.

- **Proof (cont'd):** Let Y_{even} denote the sorted even values, and Y_{odd} denote the sorted odd values.

  $Y_{even,l}$ must be larger than at least l values in Y_{odd}.
  $Y_{odd,l+1}$ must be larger than at least $l-1$ values in Y_{even}.



Batcher’s algorithm correctness

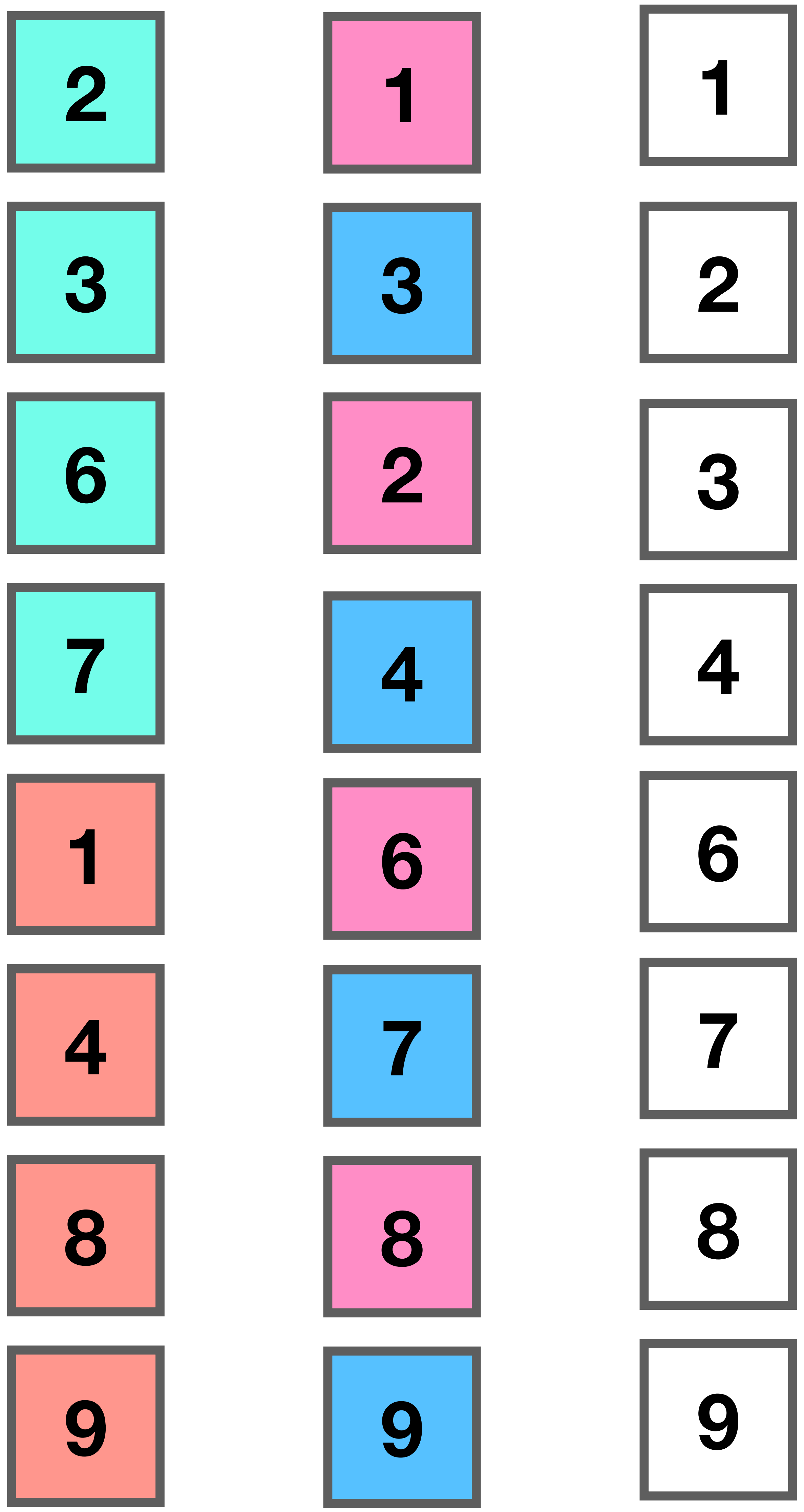
- **Theorem:** Batcher’s algorithm described on the previous slide results in a sorted list.

- **Proof (cont’d):** Let Y be the list after the 4 sorts. Let $l \in \{1, \cdots, n/2\}$. This means that

  $Y_{2l-1} \leq Y_{2l}$ and $Y_{2l-2} \leq Y_{2l+1}$ (via last slide’s argument)

  $Y_{2l-2} \leq Y_{2l}$ and $Y_{2l-1} \leq Y_{2l+1}$ (because even and odd values are sorted separately)

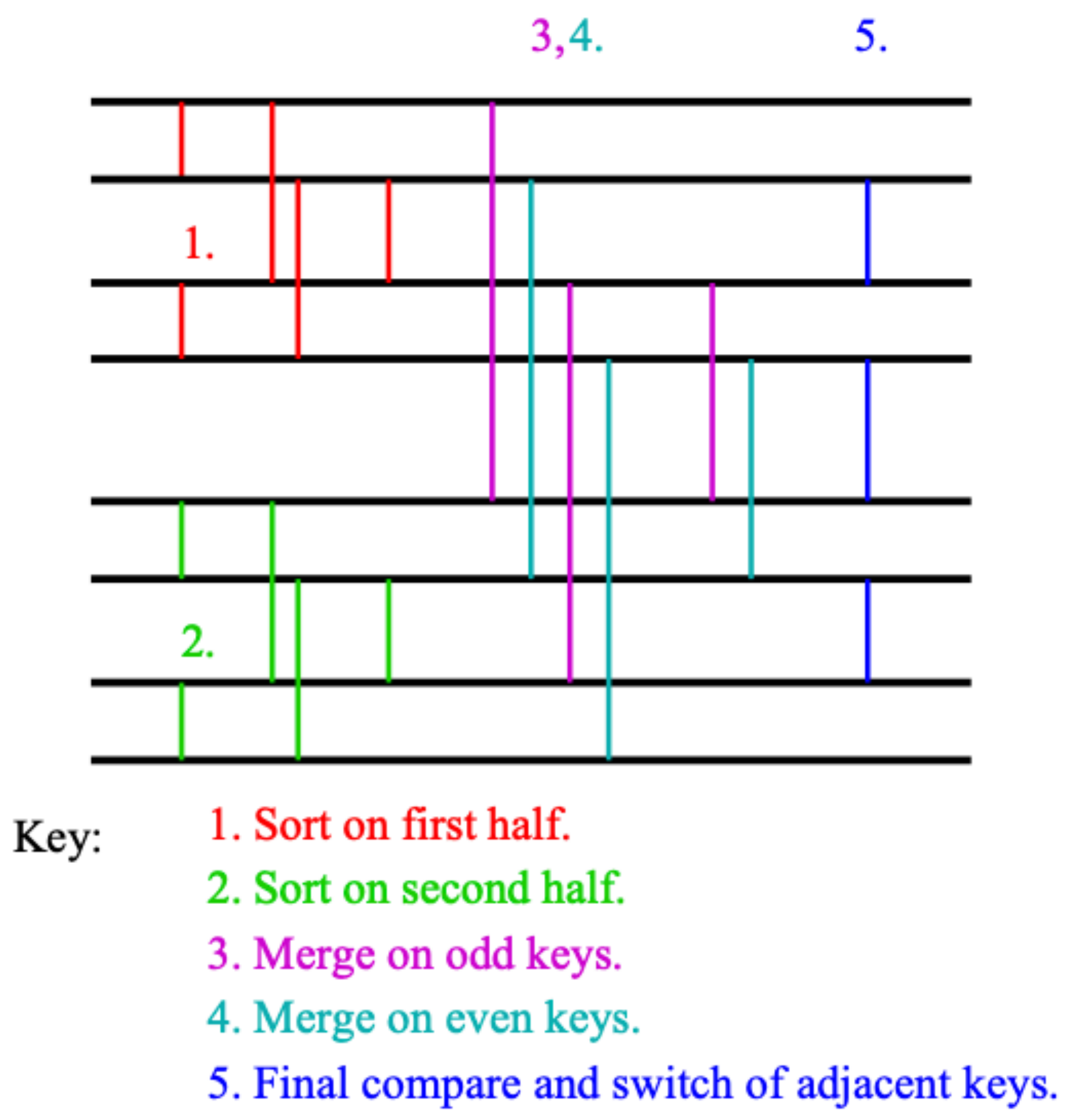
  Therefore, the elements in pairs (Y_{2l}, Y_{2l+1}) are ordered with respect to adjacent pairs. So the final step is to sort within these pairs!



Batcher's algorithm

- Applied recursively until there are only two elements, where sort = comparison

- Another optimization: after the two halves are sorted, the odd and even indexed values are partially sorted, so needs a merge instead of a full sort



Today’s readings:
oblivious analytics in SGX